CONTRIBUTED PAPER

Advances in Ground Transmitters for the NASA Deep Space Network

These transmitters are now lower-cost and have a smaller footprint, reduced cabling and improved maintainability; future development could include increased power and Ka-band operation.

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ABSTRACT | The Deep Space Network (DSN), managed by the Jet Propulsion Laboratory for NASA, is equipped with multiple microwave transmitters ranging in average radiated power from 200 W to 400 kW. The transmitters are used for routine or emergency communication with spacecraft, for navigation, and for radio science tasks. The latest advances in transmitter engineering were implemented in a new generation of 20-kW dual-band transmitters developed for the DSN 34-m beam waveguide antennas. Innovations include additional X-band communication capability for near Earth missions, new control algorithms, automated calibration, improved and expanded computerized monitoring and diagnostics, reduced cabling, and improved maintainability. The innovations were very beneficial for the DSN "overload" during the Mars 2003/2004 missions and will benefit other missions throughout the next decade. This paper describes the current design of the new transmitters and possible future developments.

KEYWORDS | Ground support; microwave; space vehicle communication; transmitter

I. INTRODUCTION

The NASA Mars Exploration Rover and other missions required additional DSN support in 2003–2004 and later. To provide the uplink portion of this support, all six 34-m beam waveguide (BWG) antennas [1] were equipped with new 20-kW transmitters. Three of the antennas were provided with transmitters covering both S- and X-band, while the others were provided only with X-band transmitters.

Previous generations of NASA high-power ground support transmitters always implemented advanced microwave tubes for radio-frequency (RF) amplification; however, the automation and control circuitry was designed using proven old technology based on electromechanical devices, analog controls, indicator lights, and direct wire connections for remote monitoring. A new BWG antenna transmitter was designed after many years of successful operation of the Jet Propulsion Laboratory (JPL)-designed 20-kW transmitters on the 70-m antenna that blended analog and digital technology for automation, control, and monitoring.

The new BWG antenna transmitters [2] fully implement ethernet communication between main subassemblies where necessary and economically reasonable. Manual controls and calibrations are minimized by deferring the tasks to a computer controller. All safety features, control functions, and data communication are implemented with dramatically reduced cabling. The new transmitters also have a smaller footprint than the old ones and better facilitate service and repair. These improvements significantly reduce costs of design, production, and lifetime support of the transmitters. Commercial hardware was used when the hardware met performance requirements and budget limitations. Overall, the new 20-kW transmitter design is a reasonable compromise between technological advances and strict budget, time, and risk constraints.

Manuscript received January 22, 2007; revised April 10, 2007. This work was supported by the National Aeronautics and Space Administration.
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Digital Object Identifier: 10.1109/JPROC.2007.905050

II. TRANSMITTER DESCRIPTION

The new BWG transmitter delivers up to 20-kW continuous-wave (CW) power to the BWG antenna feed horn in the frequency range 7145-7235 MHz (X-band) and 2025-2120 MHz (S-band).

The new transmitter consumes about 100 kW of power from the 60-Hz power grid. It is equipped with a closed-loop water-cooling circuit. The transmitter is controlled remotely and designed for unattended operation. In case of failure, most of the transmitter subassemblies may be replaced in several minutes.

Fig. 1 depicts a simplified block-diagram of the transmitter, which consists of the major assemblies briefly described below.

The power amplifiers (PAs) are located in the BWG antenna pedestal and provide amplification of the X-band or S-band phase-modulated exciter signal to any desired level between 1 W and 20 kW for commanding the spacecraft, performing navigation, or supporting radio science. Fig. 2 shows a block diagram of the PA assembly. The two-stage PA consists of a buffer amplifier assembly based on a solid-state amplifier (SSA), a high-power amplifier based on a klystron amplifier tube, an ouput waveguide system, and supporting subassemblies. Built-in commercial instrumentation includes two dual-channel power meters, a 60-channel data acquisition and switch unit, power supplies, and General Purpose Interface Bus (GPIB) and ethernet communication interfaces. The GPIB interface is

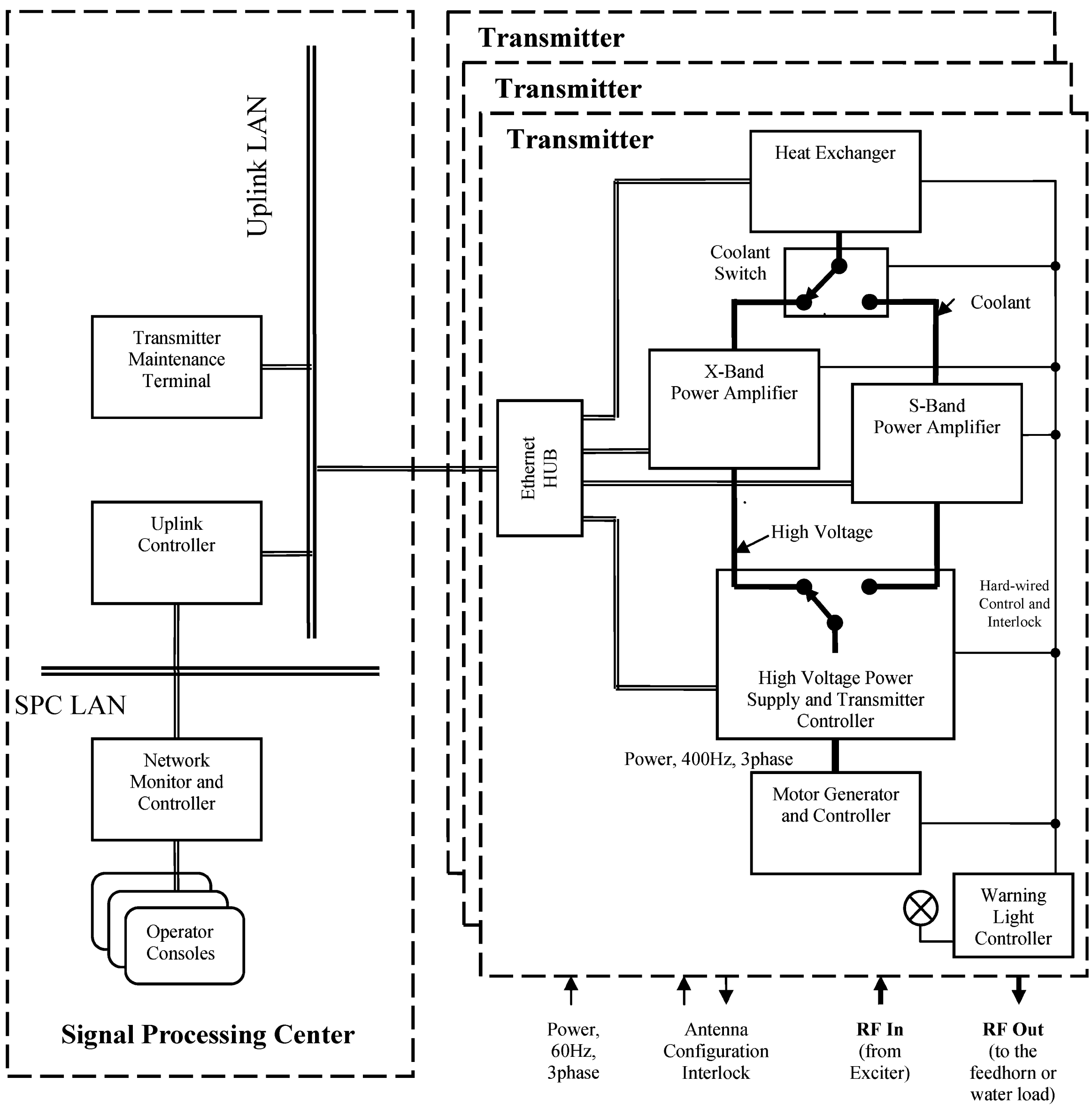

Fig. 1. *Simplified transmitter and uplink control network diagram.*

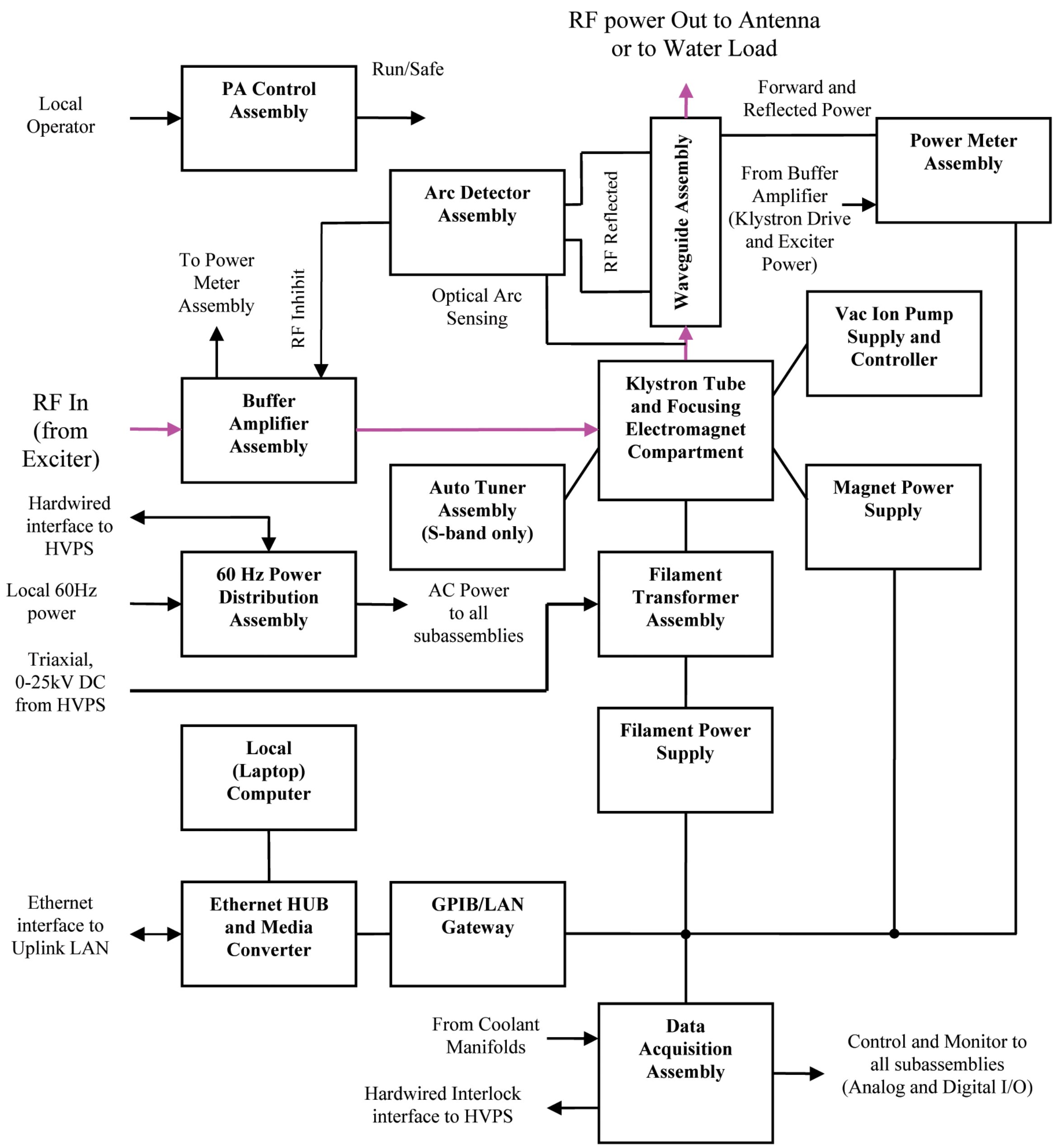

Fig. 2. *Simplified power amplifier block diagram.*

used for operational control and diagnostics of the instruments inside the PA cabinet. An ethernet interface is used for communication with the transmitter controller. The new X- and S-band PAs have identical interfaces to the transmitter controller and have similar instrumentation, magnet, and filament power supplies. Each PA includes a laptop computer used as a local display and control terminal that operates as a client to the transmitter controller. The PA design includes provisions for protecting major elements, reducing output phase noise, and increasing stability. The PAs are also equipped with waveguide filters that suppress spurious and harmonic radiation to protect the receiving equipment and to limit radio interference. Each PA delivers RF power to the respective X-band or S-band microwave subsystem. The microwave subsystem directs the power to the antenna for radiation or to a waterload for calibration and test purposes.

The X- and S-band water manifold assemblies are located near the corresponding PAs and distribute water to the various cooling circuits; provide instrumentation for water flow, temperature, and pressure; and collect the heated water for return to the heat exchanger. Instrument outputs and interlock switch status are directed to the data acquisition assembly in the corresponding PA.

A water manifold switching assembly directs water to the X- or S-band PA, depending on which of them is in use. The assembly is installed only at the stations equipped with both the X- and S-band PAs.

The water-to-air heat exchanger (HE) is located at ground level outside the antenna pedestal. It is designed to withstand the extremes of temperature conditions recorded at the three DSN complexes. The HE supplies temperature-regulated water to the transmitter. It is capable of dissipating approximately 75 kW of heat, providing the PAs with about 150 l per minute of cooling water at a pressure about 1.1 MPa.

The high-voltage power supply (HVPS) assembly is located in the antenna pedestal and provides regulated dc power (up to 25 kV with ripple below 0.01%) to the klystrons. It also includes the central transmitter controller, protective circuits, interfaces for controlling all major transmitter assemblies, and an interface for transmitter remote control.

A warning light controller located in the pedestal activates station safety warning lights when the transmitter is radiating or when high voltage is on.

The motor generator (MG) is located in an outside shelter at ground level. It converts three-phase 60-Hz power from the grid to regulated 400-Hz power (up to 75 kW) supplied to the primary of high-voltage transformer in the HVPS. The MG controller, located in the same shelter, provides protection and control for the MG.

III. INNOVATIONS

The new BWG antenna transmitters implement several improvements including computerized control, comprehensive logging of operations and greater modularity, and interchangeability of assemblies. Innovations in each of the major assemblies are described below.

A. Power Amplifier Assemblies

A new klystron amplifier tube (VA-876J from CPI) used in the X-band portion of the transmitter has a 90-MHz bandwidth covering both the deep-space and near-Earth frequency range. The VA-876P used in earlier transmitters has a 45-MHz bandwidth and required manual retuning to switch between bands. In the new X-band and S-band PAs, the tube is located in a separate compartment and mounted on a retractable support table to facilitate removal and replacement. This arrangement segregates the PA instrumentation from most of the cooling water supply in the event of a leak in the klystron cooling circuits. The S-band PA is equipped with a lifting fixture to facilitate removal and replacement of the heavy 5K70SK (CPI) klystron.

The lower gain of the VA-876J required development of a new 5-W SSA [2] to deliver adequate input power for the klystron. Providing the new SSA with an external water-cooling heat sink not only reduced the size of the buffer amplifier assembly to half that of the old air-cooled one but also has proven effective in reducing power fluctuations in the uplink signal caused by ambient air temperature variations.

Previous transmitters implemented several functions that used custom-designed circuitry. The new generation of transmitters reduces the number of custom designed circuits by including industrial test and measurement equipment in modularized assemblies. The assemblies can be used interchangeably in several different transmitters to reduce the required inventory of spare parts and to simplify maintenance. The modularized assemblies include the buffer amplifier assembly, power meter assembly, data acquisition assembly, arc detector assembly, magnet and filament power supplies, power distribution assembly, and data communications assemblies.

The use of modularized assemblies has reduced the mean time to repair the operational hardware and facilitates removal of hardware for offline service and routine calibration. In addition to self-test and diagnostic software incorporated in the commercial test and measurement hardware, additional calibration elements have been built into the same drawer in some cases. For example, the power meter assembly consists of two dual-channel power meters, their associated power sensors, and coaxial switches. The switches allow the transmitter controller to zero and calibrate the assembly each time it is powered on. The automated sequence requires about 30 s and provides long-term power measurement accuracy and eliminates tedious and unreliable manual procedures.

B. Cabling

The previous generation of DSN 20-kW transmitters used several custom-made multiconductor cables containing a total of about 400 wires to support interfaces between major transmitter assemblies. The PA control and monitor functions used almost 200 wires. The new BWG transmitters use a standard 14-conductor plenum-rated cable and a multimode fiber-optic cable. The multiconductor cable provides positive control to switch a PA on and off and to receive a safety interlock. A fiber-optic cable provides an ethernet LAN connection between the transmitter controller and the PA to control PA instruments. It also transmits data from the instruments including information regarding the status of each hardware switch in the interlock chain [3]. Each PA is also connected to the HVPS with a high-voltage cable to provide beam voltage for the klystron tube.

C. Computer Control Software

All DSN transmitters are controlled from remote signal processing centers via closed networks. In previous implementations, a remote computer system of hardware and software performed low-level control of the transmitter, e.g., setting klystron beam voltage and drive to achieve a user-specified power at user-specified frequency and high-level functions, e.g., interfacing to DSN operations and supplying monitor data to spacecraft customer. The software that performs the detailed transmitter control is now incorporated in a control computer within the transmitter's HVPS. An interface abstraction common to a wide range of transmitters was devised so that the software used by operators can implement a simplified interface to the transmitter via ethernet [2]. The interface is implemented via an IP sockets connection. The transmitter controller can support several connections to allow maintenance laptops in the PAs and a transmitter maintenance terminal near the operators to monitor and control the operation of the transmitter (see Fig. 1). The transmitter is self-protected against loss of ethernet communication or computer hardware failure; it safely shuts itself off.

The control software uses a structured query language (SQL) server to maintain transmitter calibration data and to store a record of critical events and transmitter performance data averaged over one-minute intervals. The parameter-logging function records the value of approximately 105 parameters once per second. The control software provides the ability to plot the different operational parameters with 1 second resolution as a function of time over the previous 1000 s. Additionally, if an interlock occurs, a file containing all parameters collected 990 s before and until 10 s after the interlock is saved. The SQL server is network-enabled and can be queried remotely. On a daily basis, the transmitter maintenance terminal automatically queries each of the transmitters at the tracking complex for the previous day's log files and sends them to JPL engineering. The engineering group performs ongoing analysis to spot performance trends and to help maintenance personnel to resolve any problems. These data have been valuable in reducing the transmitter failure rate by half from the time of initial installation [4].

D. High-Voltage Power Supply

The control, interface, and indication systems of the HVPS were fully upgraded from the systems used in old transmitters. The computer interface provides all routine control operations while only a few manual switches and indication lights are needed to facilitate troubleshooting, testing, and calibration and to assure safety during maintenance.

Many of the mechanical relays were replaced with solid-state optically isolated modules. A digital-to-analog

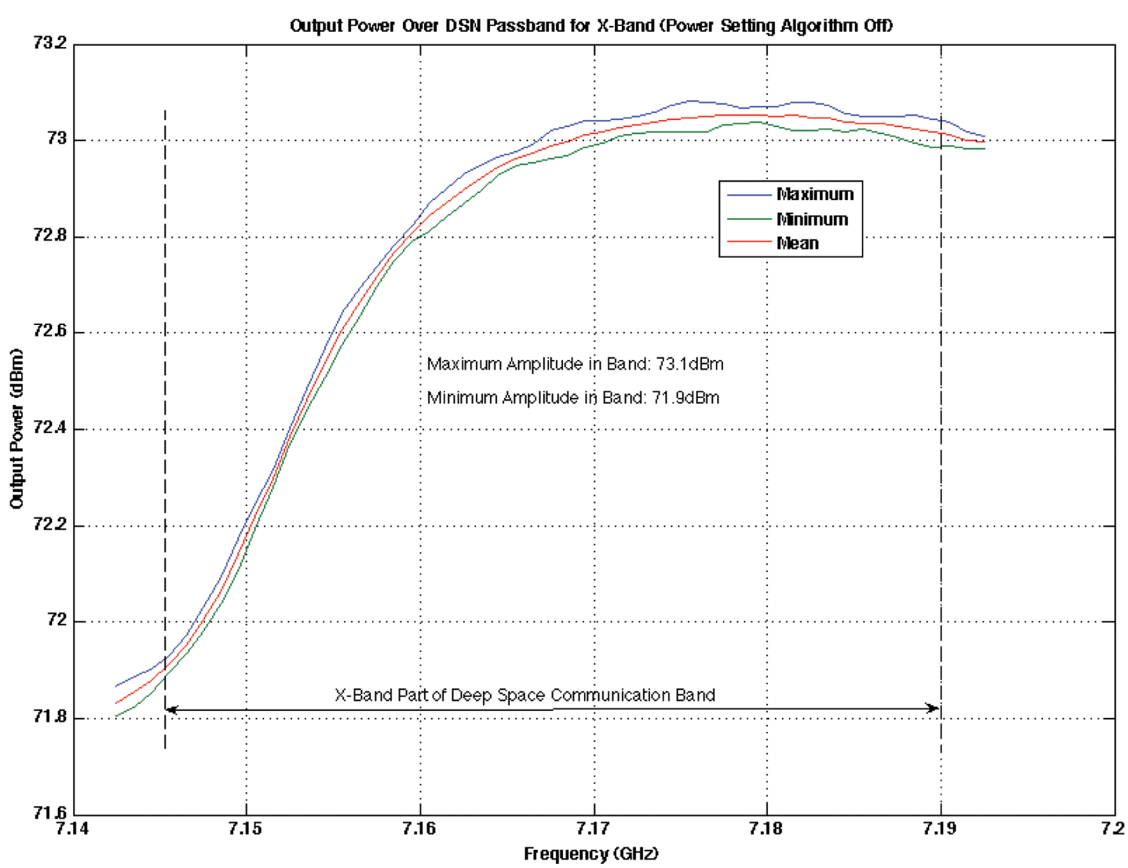

Fig. 3. ***X-band power output variation during 15-h stability test.***

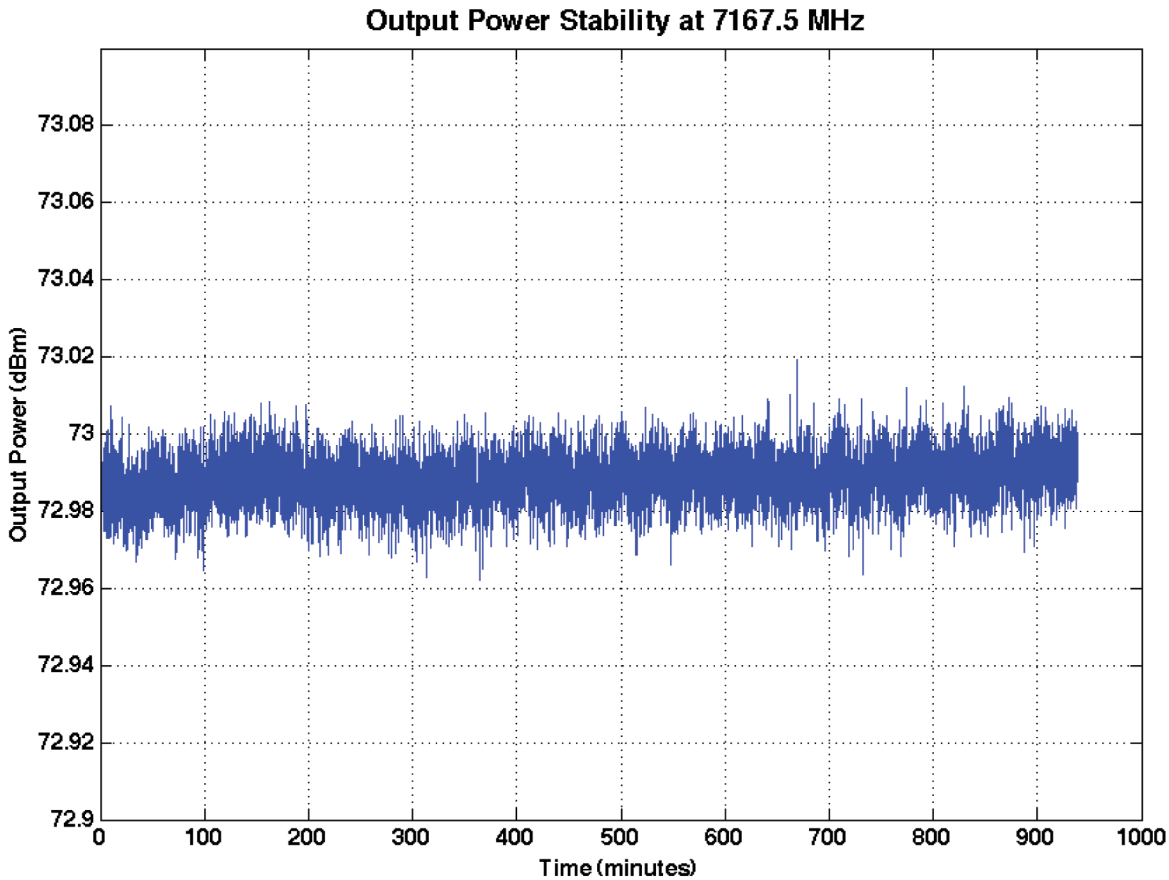

Fig. 4. *Long-term amplitude stability (requirement is less than 0.1 dB).*

converter coupled with an isolation amplifier replaced a stepper motor and potentiometer used to adjust beam voltage in older transmitters. The new HVPS has built-in calibration and test circuits that significantly simplify maintenance and reduce the time required for meter calibration or interlock trip level adjustments.

Overall, the new design achieves a 25% reduction in size along with significantly reduced internal and external wiring and better access to subassemblies. The results are simplified service and maintenance and increased safety.

The control software used in the old transmitters required initial calibration of a klystron that required almost eight hours of constructing a reference table for software to use later to set beam voltage and drive for a particular track. Even with this table, the old system required about six minutes to arrive at the proper combination of beam voltage and drive. The calibration table also had to be updated periodically to account for aging of the klystron and associated transmitter components.

The new embedded controller uses an algorithm [2] to determine the optimum beam voltage and drive to dynamically achieve either saturated or nonsaturated klystron operation as directed by the uplink controller. Experience has shown that the algorithm converges to the desired power within three minutes or less without requiring the extensive preoperation calibration and periodic recalibration previously needed.

E. Heat Exchanger and Cooling Circuits

Based on safety, environmental, and tube longevity considerations, pure water is the coolant of choice for modern high-power DSN transmitters. Alternatives have been discarded. Ethylene glycol presents health hazards. The viscosity of propylene glycol does not allow enough turbulent flow to adequately cool the X-band klystrons used.

Freeze protection of the heat exchanger is achieved by simply circulating water. The heat generated by the pumps and friction in the piping is adequate to maintain water above freezing throughout the system. As a backup to software protection, an auxiliary control card was added to force the pumps to start if the controller fails to start them. The same card will force the cooling fans to operate at full speed if the water temperature rises above approximately 71 °C.

Water manifolds for the new BWG transmitters have been completely redesigned. Any element can now be replaced in minutes and possible leaks are minimized. The new design implements automatic flow regulators. Once adjusted at initial setup, water flow in every heat removing circuit never changes. Adjustments required by the old design after component replacement have been eliminated. Each circuit is equipped with a reliable flow meter to provide local and remote flow-rate readings and with a flow sensor with an adjustable threshold to shut down the transmitter in case of reduced water flow. Bimetallic switches are included to shut down the PA if the maximum allowable temperature in the klystron collector cooling circuit is exceeded.

The collector/load cooling circuit has a built-in calorimeter for transmitter self-test and calibration. The calorimeter is easily calibrated against verified electrical readings and is monitored by the transmitter controller. For increased accuracy, the computer processes resistive temperature detector readings to eliminate any initial offset.

Critical cooling circuits are equipped with replaceable filters for particulate removal. Water quality is critical for the VA-876J klystrons and is maintained by controlling water resistivity and pH. For the new generation of 20-kW transmitters, a water quality monitoring and maintenance protocol keeps water resistivity between 10 and 100 kΩ–cm and pH between 7.0 and 8.5 to reduce corrosion and eliminate scaling. The protocol significantly improves transmitter availability and increases tube life.

IV. PERFORMANCE

The transmitter meets stringent requirements for low out-of-band radiation and phase noise (defined for low frequencies in terms of additive Allan deviation), while providing high amplitude, phase, and group delay stability.

Long-term (> 12 h) stability tests are performed with a test set that includes 1) a control computer with custom data collection and analysis software and 2) a vector network analyzer that injects a frequency ramp at the input of the transmitter and measures the resultant amplitude and phase at the transmitter output directional coupler.

At the beginning of the test, the power output of the transmitter was set for saturated operation at approximately

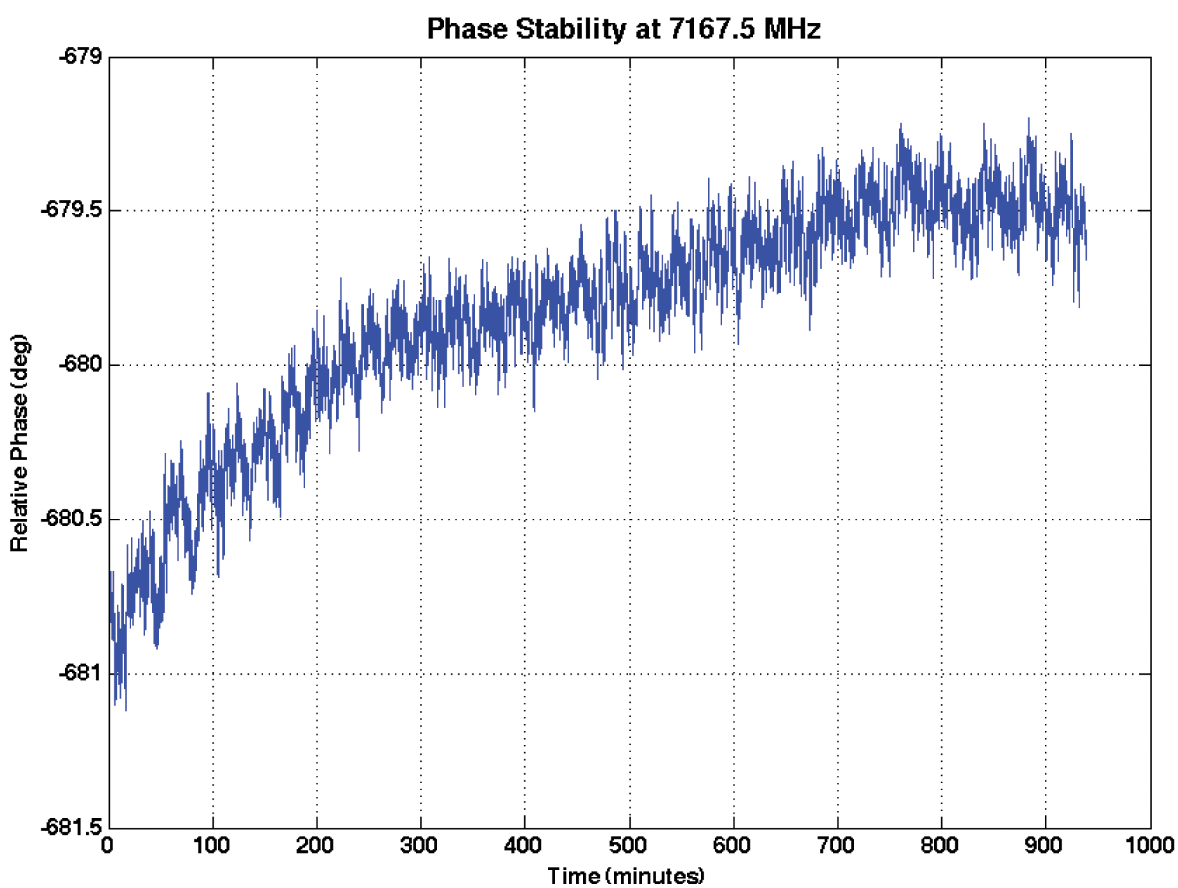

Fig. 5. *Long-term phase stability (requirement is 23° rms over 60 s and 295° over 12 h).*

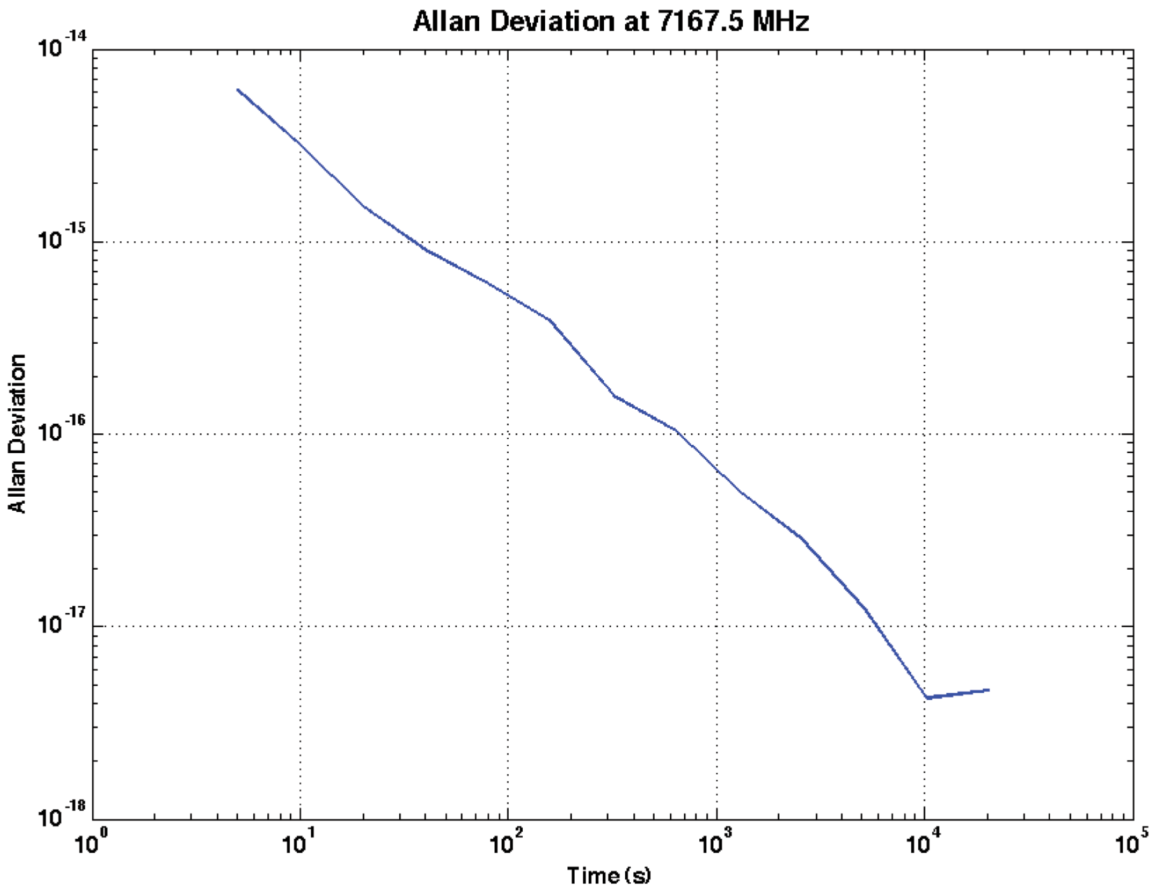

Fig. 6. *Allan deviation (requirement is 1.7e-14 at 10 s and 1.2e-15 at 1000–3600 s).*

20-kW CW at the center of the band. The network analyzer was then switched to sweep mode with stabilized output power. The curves in Fig. 3 show the response of the transmitter RF chain over a 15-h period.

Figs. 4 and 5 show the power output stability and phase stability at one of the frequencies used in the test. The measured performance exceeds requirements by approximately a factor of five for amplitude stability and two orders of magnitude for phase stability.

Fig. 6 shows the additive Allan deviation. The results are better than requirements by approximately an order of magnitude.

Results for S-band operation are similar to those shown in Figs. 3–6 for X-band because the high-voltage regulation and temperature regulation are common to both PAs.

Transmitter group delay stability (over 12 h) was measured to be approximately three times better than the requirements for both S- and X-band.

A realistic measure of the transmitter performance in an operational environment was obtained with a computer-controlled synthesizer as a stimulus and the transmitter's built-in logging capability to measure forward and reflected power, body current, water flow, coolant temperature, etc. A control program sets the synthesizer frequency and commands the transmitter automatic power setting capability to step through the entire frequency band at small intervals (e.g., 100 kHz to 1 MHz). At each frequency, the transmitter was operated at 20 kW for several minutes. This procedure also allows thorough testing of high-power components at full power for different frequencies including those suspected as local resonances (if any). The "step test" may also be used on operational systems to compare transmitter performance over time with the original equipment. Figs. 7 and 8 demonstrate X-band and S-band performance, respectively. Results show that the power setting algorithm compensates for variations in klystron gain with frequency and provides the required transmitter instantaneous bandwidth.

V. FUTURE DEVELOPMENT

The BWG transmitter design was a fast, low-risk, low-budget project. Some innovations remain to be implemented. One is replacement of the bulky MGs by compact solid-state power converters. The regulated converter would include an active rectifier, dc bus, and 400-Hz

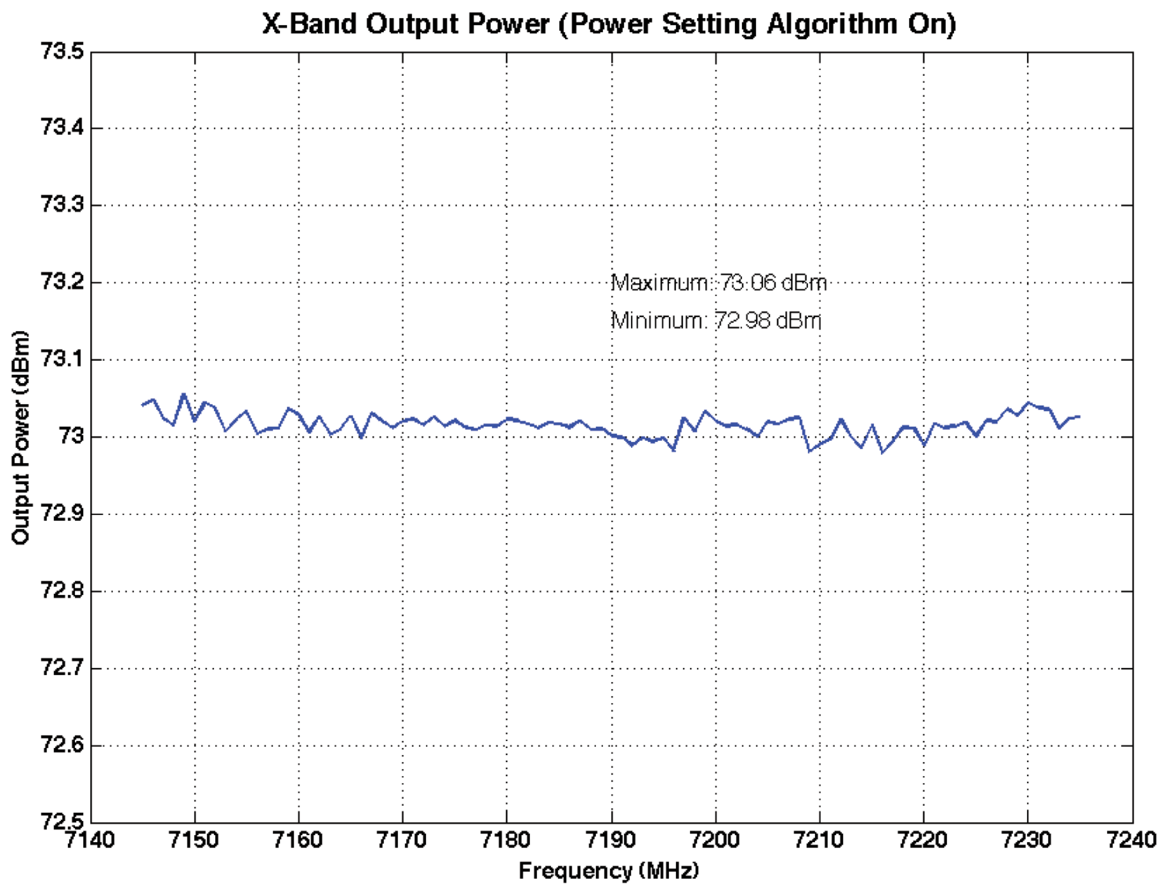

Fig. 7. *Forward power over entire X-band operational bandwidth.*

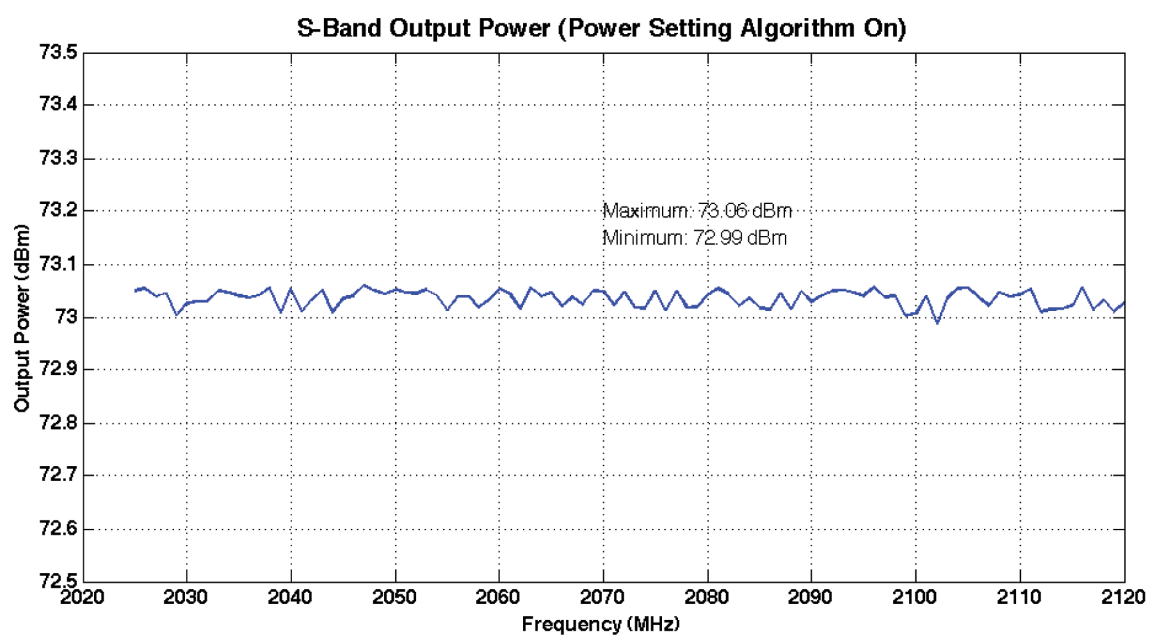

Fig. 8. *Forward power over entire S-band operational bandwidth.*

inverter to supply power to the conventional linear high-voltage power supply. An alternative may include replacement of the linear high-voltage power supply with a regulated switching power supply to significantly reduce power supply physical dimensions. Implementation of such well-developed technologies in DSN transmitters requires research to confirm that high reliability, stability, and low phase noise requirements are satisfied.

Because a high-power microwave transmitter combines many different technologies from water chemistry to high-voltage engineering to computer science in one complex installation, it usually requires highly experienced personnel to repair and maintain. Maintenance and staffing problems could be reduced in the next generation of the DSN transmitters by implementation of automated test and calibration capabilities, remote diagnostics, modularity, and standardization. The availability of new DSN transmitters could be improved further by adding redundant elements with a reconfiguration capability that minimizes degradation of uplink performance after a failure of any major assembly. One such project, a modular 100-kW BWG transmitter, is under study.

Transmitter operations and maintenance will be simplified and made more reliable by increasing the commonality of the hardware and software. The BWG implementation is an indication of the usefulness of converting all fielded DSN transmitters to ethernet-based control interfaces and implementing enhanced data capture and reporting.

The DSN currently supports spacecraft uplinks at S- and X-band. Some of those transmitters and the antennas on which they are mounted are at the end of their useful life and require replacement. The growing fleet of spacecraft demands increased support. To satisfy these needs, significant future development is needed. Possible enhancements include:

- implementation of 100-kW transmitters in BWG as a possible replacement for 20-kW transmitters on the 70-m antennas;
- incorporation of 20 kW S-band transmitters in all BWG antennas to support communication with lunar exploration crewed vehicles;
- Ka-band transmitters with outputs of 5 kW or higher;
- emergency commanding at powers of 350 kW to 2 MW;
- use of multimegawatt pulsed transmitters for communication with spacecraft at the edges of the solar system and in interstellar space.

Significant developments in solid-state microwave devices may make their use in high-power applications economically and technically feasible.

The next generation of the DSN may include arrays of uplink antennas, active antenna tiles, new antenna configurations, etc. All this will require new transmitter development. ■

Acknowledgment

The authors would like to thank T. Cornish, G. McDowall, J. Ocampo, and A. Santos for their contributions to the transmitter design and for help with manufacturing, integration, and test of the delivered transmitters.

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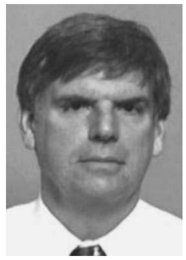

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